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Suspended Matter Distributions and Fluxes Related to the Hudson-Raritan Estuarine Plume

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Rockville, Maryland
December 1984

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Suspended Matter Distributions and Fluxes Related to the Hudson-Raritan Estuarine Plume

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ABSTRACT. Particle flux through the New York Bight apex was calculated using current meter and suspended matter concentration data obtained from March to September 1979, to gain insight into the particle dynamics within the Hudson-Raritan estuarine plume discharged on the shelf. Suspended particulate matter (SPM) concentrations show the expected rapid decrease seaward (10 to 1 mg/ℓ), but high concentrations often extended seaward around Shrewsbury Rocks on the New Jersey shore. Flux calculations and spatial concentration plots indicate that the quantity of SPM carried by the Hudson plume is probably of the same order as or less than the SPM flux through the adjacent Long Island shelf, except during spring runoff. High values of flux during runoff were due primarily to increased water flow rather than increased SPM concentration. Sampling during a September storm indicates that a single meteorological event can produce SPM fluxes in the plume comparable to spring runoff values. Storm events of this magnitude or greater probably occur a few tens of times during a typical year.

1. INTRODUCTION

River plumes, such as that formed by the discharge of the Hudson-Raritan estuary into the New York Bight, are one of the principal vehicles for transport of fine-grained sediment to the coastal oceans. The importance of the Hudson River plume is that pollutants associated with the suspended matter are thus introduced into the New York Bight, an area used intensively by man for recreation and as a fishery (Squires 1981). This study describes the spatial and temporal distributions of the Hudson River particle plume in the inner New York Bight (Figure 1). It is based on flux calculations from current meter observations and concurrent measurements of suspended particulate matter obtained over an eight-month period during 1979.

Other studies have compared suspended particulate matter values in the New York Bight with selected sites along the Atlantic coastline from Cape Cod to the Florida Keys (Mannheim et al., 1970; Meade et al., 1975). Relative to the rest of the coastline, the Bight is known to have higher suspended particulate matter values, ($\sim$4 mg/ℓ on the average).

Concentration and current velocity data were combined to produce temporally and spatially averaged estimates of suspended matter fluxes. These fluxes, in addition to plots of temperature, salinity, and sigma-t, were used to examine the spatial and temporal distribution of particulates discharged from the Hudson-Raritan estuary.

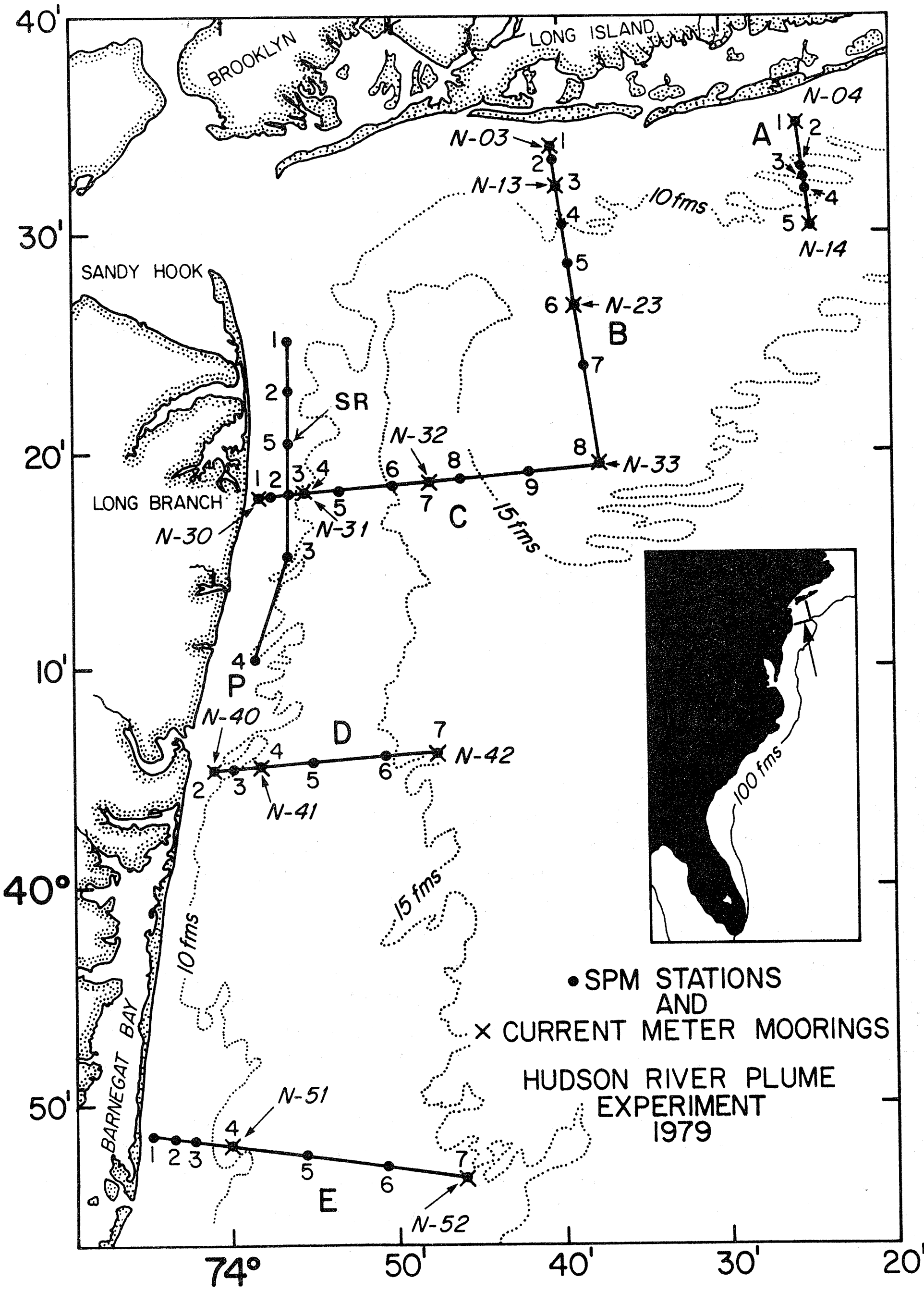

Figure 1. Location map of water-sampling stations and current meter moorings in the New York Bight. Current meters are designated (N-) and water-sampling stations are numbered along each transect. SR is the location of Shrewsbury Rocks, a local shoal extending from near shore to about the 10 m isobath.

1.1 Background

1.1.1 Physical characteristics of the plume and shelf circulation

Several circulation studies (Kao, 1975; Charnell and Hansen, 1974; Beardsley et al., 1976; Charnell and Mayer, 1975) indicate that the Hudson-Raritan estuary is a two-layer, partially mixed estuarine system. This concept is detailed in Beardsley and Hart (1978). Generally, the denser, more saline bottom waters migrate into the estuary via the dredged navigation channels (Rockaway, Ambrose, and Sandy Hook), as well as penetrating to the near surface in the northern (Rockaway, New York) end of the transect. Typically, the low-salinity, high-turbidity, surface plume is confined to the southern three-quarters of the Rockaway-Sandy Hook transect. On average the plume extends to a depth of eight meters below surface (Hansen, 1977; Bowman, 1978). Some studies (Duedall et al., 1977; McLaughlin et al., 1975) suggest the net flux of suspended particulate matter as being positive into the Bight. Other studies (D.J.P. Swift, personal communications) indicate a slightly negative flux into the estuary.

Upon discharge from the estuary, inertial and Coriolis forces direct the plume southward where partial entrainment by the net southwest flow of the shelf waters results in a coast-parallel flow. This southern direction is prevalent during seasonal peak periods of river discharge. With the exception of Shrewsbury Rocks extending seaward from shore at the southern end of Sandy Hook, New Jersey (Figure 1), few obstructions inhibit the plume as it flows southward.

The particulate plume is generally within five to ten km of shore (Drake, 1974; Drake, 1977; Nelsen, 1979). Figure 2 shows the southern extent of the plume following a flood tide during midsummer 1972, a time of low river discharge and primary productivity. During spring thaws and heavy rains, the southern extent may be considerably greater. Average surface concentrations of 1-10 mg/ℓ have been observed in the plume (Drake, 1974), and values obtained during this study were also within this range. The thickness of the fresher (26-31°/₀₀) surface water varies from nearly four meters at the estuary mouth to zero at a point of complete mixing with more saline shelf waters (>31°/₀₀) about 40 km from the Hudson-Raritan estuary (Bowman, 1978).

The usual orientation of the plume is parallel to the New Jersey coast (Figure 2). A change in wind stress direction will affect inner shelf waters typically within about six hours (Han and Mayer, 1981). Complex interdigitations and spreading toward Long Island occur when winds originate from the southwest-to-west octant, and during periods of low discharge. Regardless of mixing and dispersion processes in the Bight apex, the general circulation of shelf waters tends to confine the plume along the New Jersey shore, and entrainment and mixing processes cause dilution and dispersion into shelf waters toward the south and east.

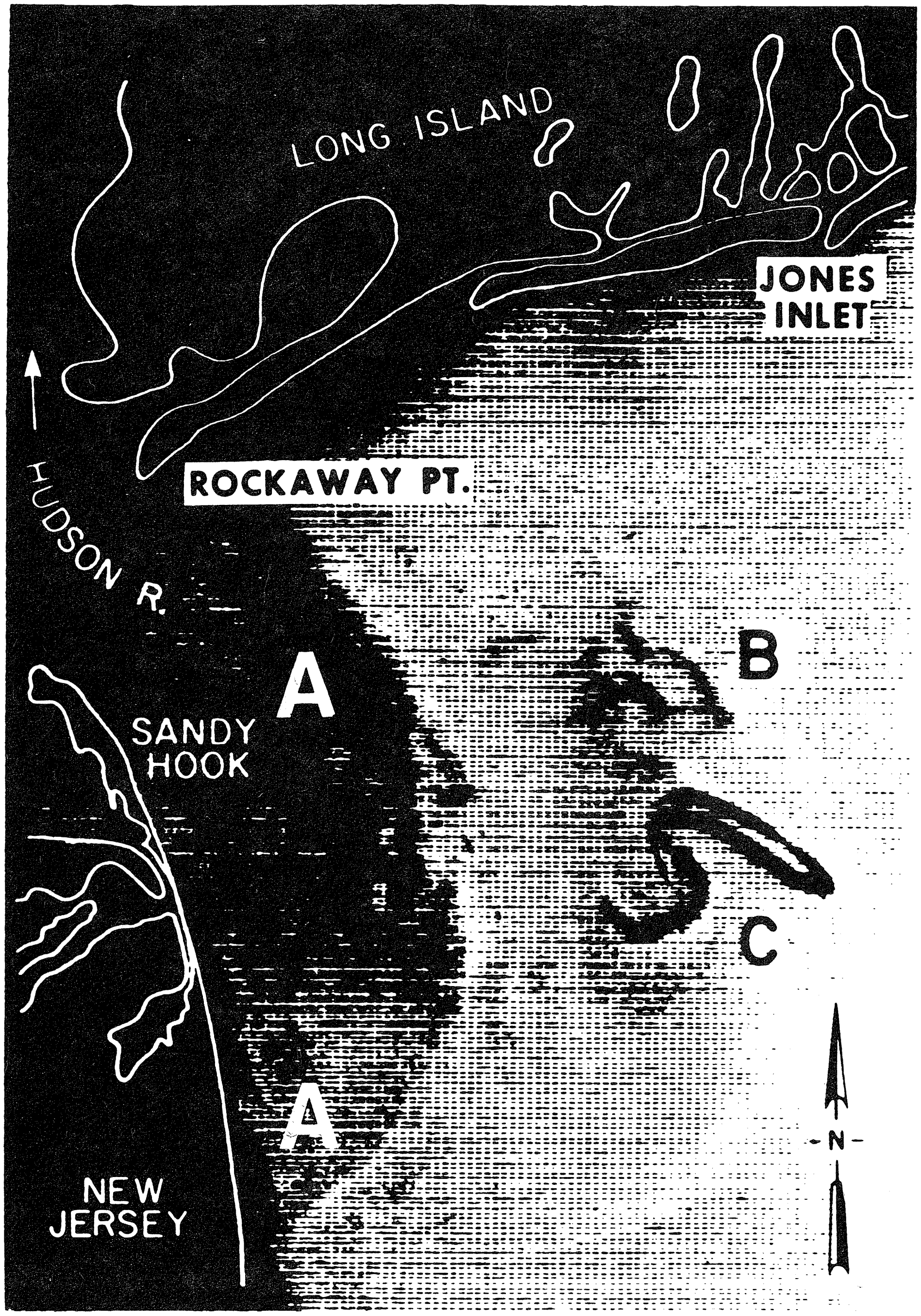

Figure 2. ERTS satellite image of the New York Bight, including: (A) the Hudson River plume, (B) the trail of a recent dredge-spoil dump, and (C) similar trails of two recent acid waste dumps. The image was taken August, 1972 at a wavelength of 0.6 - 0.7 μm; uncorrected for geometry; convolution by a 3 x 3 boxcar filter.

1.1.2 Distribution and composition of suspended particulate matter (SPM) in the Bight

Several previous descriptions of the plume are based on distributions of suspended particulate matter determined during investigations of dumpsites in the Bight (Betzer, 1978; Garside et al., 1976). These distributions of suspended particulate matter were related to river input, primary productivity, sediment-water interactions, and most notably, to the dumping of anthropogenic waste materials.

Basic differences between bottom and surface suspended particulate matter compositions are noted. Surface suspended particulates were found to be organic-rich (>50% organic material) while bottom sediments were mostly inorganic (<10% organic), typical of most open-shelf environments (Betzer, 1978; Nelsen, 1979; Drake, 1974). In addition, Betzer (1978) observes that areas dominated by actively photosynthesizing diatoms (i.e., the plume) had very low levels of most particulate trace metals. Contaminant metals such as Cu and Zn apparently do not accumulate in the apex but are removed to either shelf waters or are recycled to the estuary via the returning deeper waters. Drake (1974, 1977) concurs with Mannheim et al. (1970) concerning the association of abundant opaque black grains in the "turbid plume emanating from the Hudson River" and relates them (optically) to black soot, derived from sewage disposal.

Particle-pollutant associations developed as SPM passes through the estuary may ultimately control the nature of the suspended matter discharged from the estuary. Meade et al. (1975) discuss the limited interaction of river-derived sediments with waters of the rest of the shelf. Their conclusion was that most of the inorganic material in suspension is a result of resuspension by storm waves. This is supported by later studies (Young et al., 1981). It has also been proposed that estuaries serve as a trap for fine sediments, brought in by rivers and from inner shelf waters (Meade, 1969). Repeated cycling of SPM through the estuary is likely (Garside et al., 1976) allowing numerous contacts between pollutants and particles. A portion of the particle load is removed continuously from the system by deposition in the estuary or by discharge down-coast in the river plume. This holds true in the Hudson plume as in most river-estuary-shelf systems.

Mannheim et al., (1970) cite hydrated iron-oxide aggregates used to trace the mixing of river waters with shelf waters. Ketchum et al., (1951) estimate the iron contribution from the Hudson estuary at 40 to 50 tons/day. Iron and manganese are ubiquitous as hydrous oxide particles in the Bight and are observed most frequently in New Jersey nearshore waters (Biscaye and Olsen, 1976). These metals act as mediators for adsorption and biologic transport of inorganic pollutants.

Studies of input levels of contaminants into the estuary and Bight apex are numerous (Intorre and Derienzo, 1974; Olsen et al., 1978). These studies show the geochemical and compositional makeup of sediments found within the estuary, the input of contaminants due to maintenance and cleaning of power plants, and other industrial contributions. Radionuclide and synthetic organic pollutants are associated with the SPM because of the high adsorptive capacity of fine-grained particles.

Coprostanol, a sterol produced in the mammalian gut, is one such indicator that has been used to interpret the origin of fine particles in the Bight (Hatcher and McGillivary, 1979). Such an indicator is useful in assessing the interaction of plume waters with shelf waters that contain various dumpsites (sewage, acid waste, dredge spoil). Polluted particles are also discharged through inlets along the New Jersey and Long Island shoreline. This interaction is sometimes misleading as plume-derived, fine-grained particles, accumulating in depressions along the New Jersey coast, are sometimes found mixed with anthropogenic radionuclides that have been locally expelled through estuarine inlets along the coastline, such as Barnegat Inlet (Olsen et al, 1980). Thus far, there is little evidence that dumpsite materials are entrained by the southward-flowing plume (Drake, 1974). The best tracers, to date, for tracking the dispersive paths of the plume are iron-titanium oxide coatings and titanium oxide particles that are precipitated as particles pass through the estuary (Biscaye and Olsen, 1976).

These trace metals and their related compounds are not sufficient in themselves to adequately define particle dispersion paths and sediment transport processes. However, the flux of total SPM in the plume can indicate the rate, frequency, and pathways of several classes of pollutants entering the Bight. A breakdown of each pollutant type and quantity requires a much more detailed study.

2. METHODS

Current meter moorings were deployed along five transects in the study area (Figure 1). Most moorings had one near-bottom and one near-surface current meter; on some a third, midwater meter was also installed. Arrays were deployed for periods of six to nine months during the study period. Approximately once per month, water samples were taken at 32 stations along the array transects to obtain suspended matter concentrations (Table 1). In addition, salinity, temperature, and light-scattering profiles were obtained at most water-sampling stations for most cruises (Mann, 1980). During the last cruise (Neph 8, September) a short-lived storm afforded the opportunity to study the effects of a high-energy meteorological event on the suspended matter of the inner Bight.

2.1 Current Meter Observation

All but three of the current meters used were Savonius rotor (Aanderaa Model RCM-4) types which recorded total rotor revolutions and a single direction during a preset ten-minute sampling interval. Current meters were mounted on wave-dampening spar buoys to obtain measurements three meters below the water surface. Near-bottom meters were typically placed one to five meters above bottom.

Shallow water current measurements using a Savonius Rotor are subject to considerable error from surface waves, mooring motions, and especially rotor spin up. The latter is caused by orbital-wave velocities superimposed on the mean flow which produce little change in mean water velocity but "pump" the rotor, giving higher apparent mean speeds than really exist. Therefore, the shallowest (inshore) array of each shore-normal transect consisted of a Marsh-McBirney (Model 585) two-axis electromagnetic current meter mounted on

Table 1. Summary of Cruise Statistics

Neph Cruise Number	Dates of Cruise (1979)	No. Stations Occupied	No. Water Samples Taken
1	13-15 March	32	62
2	04-05 April	34	65
4	21-23 May	33	97
5	10-11 June	34	102
6	29-30 June	37	74
7	01-02 August	37	72
8	05-07 September	39*	90

*13 of the stations were occupied twice during the cruise, once before and once after a major storm.

a bottom tripod with the sensor one meter above bottom. These inshore endpoints did not have an accompanying surface meter.

All Aanderaa flow data were resolved into north and east components, edited for spurious values, smoothed out by a low-pass (three hour) filter and resampled at one-hour intervals. The inshore Marsh-McBirney meters internally record the east and north flow components once per second for periods of two to three minutes every two hours. Mean speed and direction can be calculated by removing the orbital velocity components of flow. In addition to the standard processing techniques, the tidal component of flow was removed by subtracting the predicted tidal current components referenced from tides at Sandy Hook, New Jersey. This detided data was the basis of all subsequent flux calculations.

Not all moorings were deployed during each water-sampling cruise (Figure 3). Conversely, some moorings having current velocity data for a given cruise lacked the necessary concentration measurements to compute flux.

2.2 SPM Concentration Measurements

Suspended-particulate-matter measurements were made by direct water sampling and filtration onto Nuclepore filters (0.4 μm), and by continuous light-scattering profiles. Details of the sampling procedures and all data are given in Mann (1980). Ten-liter Niskin sampling bottles were mounted on a standard rosette frame. Salinity and temperature profiles were obtained concurrently with a CSTD probe (Interocean Model 513-D) that was mounted on the same rosette frame that carried the water-sampling bottles. The resultant profiles were plotted by computer and used to determine pycnocline depth during each cruise.

Continuous light-scattering profiles were obtained with an optical turbidimeter (Monitek Model 350/136), also attached to the rosette frame. These profiles were helpful in determining the vertical distribution of suspended matter.

All field work was carried out on the NOAA Ship KELEZ. Water-sampling and current meter deployments took place during each cruise. Navigation for all field operations was by Raydist in range/range mode with LORAN C as a backup.

2.3 Hudson River Discharge Rates

The long-term (30 year) average runoff of the Hudson River gauged at the Battery is 1.42×10^9 m^3 per month (4.6×10^5 ft^3/sec; Geise and Barr, 1967). Deviation from this mean value is considerable and frequent, especially during the peak runoff period in late spring/early summer (Figure 4). About one-half of the annual runoff during a typical year occurs during March to May, when the monthly average may exceed the long-term average by a factor of four or more (Bowman, 1978). The year 1979 (Figure 4) appears to be fairly typical as only two monthly values (January and March) fall outside the range of the 30-year mean.

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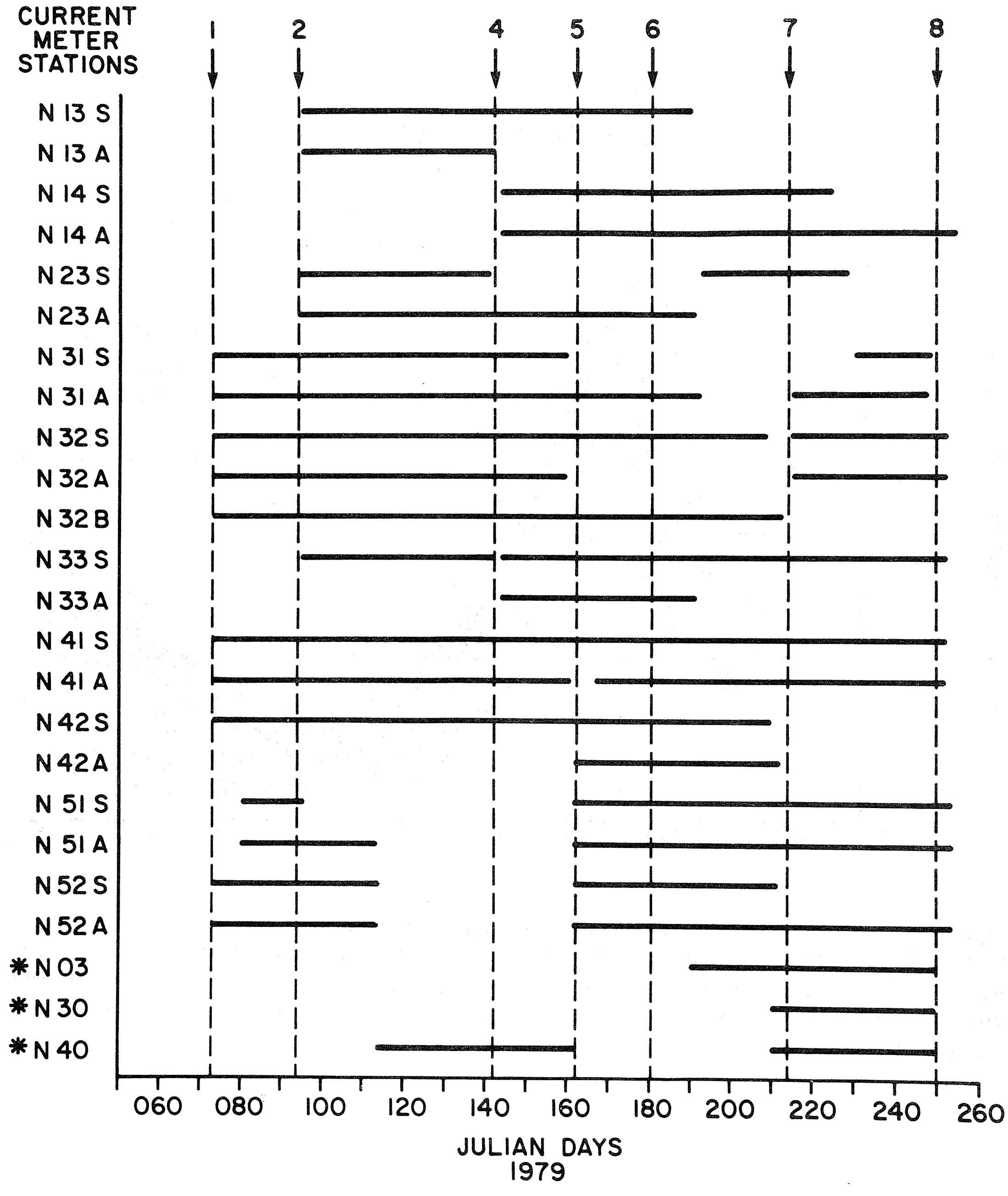

Figure 3. Intervals of current meter deployments. Near-surface meters are designated by an (S) and bottom meters by an (A). N32A, however, is a midwater meter and N32B the bottom meter. (*) denotes an electromagnetic-type current meter.

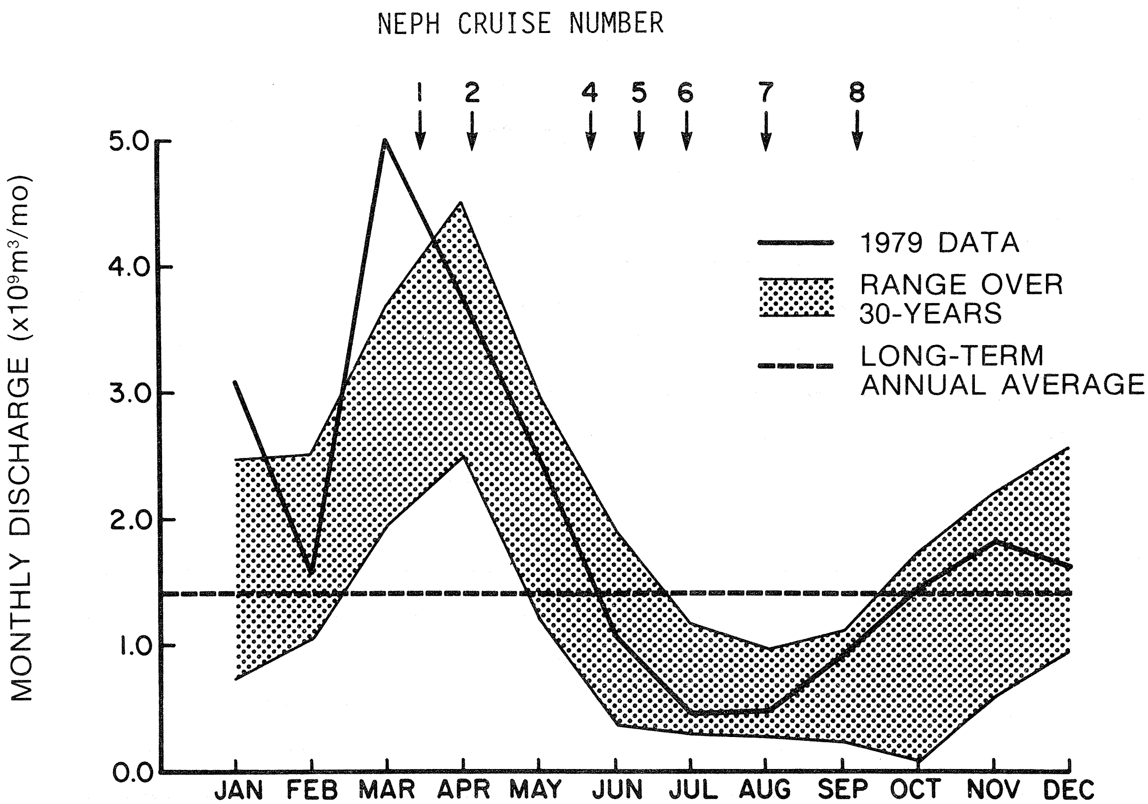

Figure 4. Monthly water discharge for the Hudson River at the Battery during 1979, and the range of monthly discharge over the previous 30 years. (Data from the USGS, Water Resources Division.) the long-term average, annual discharge, is 1.42×10^9 m^3/mo (4.6×10^5 ft^3/sec; Giese and Barr, 1967).

2.4 Wind Data

Wind data obtained from nearby John F. Kennedy Airport on the south shore of Long Island was digitized at three-hour intervals and average wind speeds and direction were determined for each cruise period. Average winds were less than 5 m/sec. Han and Mayer (1981) describe the correlation of wind stress components with observed surface current patterns for previous years in the Bight and indicates reasonably strong dependence of flow direction and speed on the winds.

2.5 Flux Calculations

Advective flux, F, through a unit volume can be calculated as

$$F = U \times C \qquad (1)$$

where the instantaneous horizontal flow velocity U and concentration C terms in that unit volume can be defined by the sum of their temporal mean values ($\overline{C}$, $\overline{U}$) and turbulent fluctuations around the mean (C', U'), or

$$U = \overline{U} + U'$$

$$C = \overline{C} + C' \qquad (2)$$

Substituting (2) into (1), time-averaging and rewriting gives the familiar result

$$\overline{UC} = \overline{U}\,\overline{C} + \overline{U'C'} + \overline{U'\overline{C}} + \overline{\overline{U}C'} = \overline{U}\,\overline{C} + \overline{U'C'} + \overline{U'}\,\overline{C} + \overline{U}\,\overline{C'} \qquad (3)$$

where the overbars indicate time averages. Settling of particles is neglected in this approach.

The averaged quantities $\overline{U'}$ and $\overline{C'}$ tend to zero by definition, leaving

$$\overline{UC} = \overline{U}\,\overline{C} + \overline{U'C'} \qquad (4)$$

The term $\overline{U'C'}$ remains because fluctuations in velocity are related to changes in turbulent shearing stresses in the moving fluid which tend to keep particles in suspension and increase the rate of bottom erosion. Thus, U' and C' are at least partially correlated and their product is non-zero.

Flux calculations for this study do not include the term $\overline{U'C'}$. While mean values of concentration of suspended matter and water flow may be reasonably estimated over short sampling periods by the methods used in the present study, it is more difficult to assess their respective fluctuating components, especially for the suspended matter. Previous work indicates that $\overline{C}$ is systematically related to both C' and U' (Young et al., 1981; Lesht et al., 1981; Clarke et al., 1982). It was felt that typical water-sampling periods of two days per cruise did not afford enough concentration data to accurately determine C' at relevant time scales, although sufficient current meter data exist to evaluate U'. However, these relationships will become useful in obtaining time-averaged estimates of flux from larger (concentration) sample populations. For purposes of describing the plume, we felt it adequate to use flux computations based on average values ($\bar{U}$, $\bar{C}$) only, so the estimates given here must be viewed as internally consistent, but relative, values.

To calculate flux from point measurements, it was necessary to define cross-sectional areas and subareas for each transect shown in Figure 1. Figure 5 shows a typical cross section of a transect used in the study. Transects were subdivided vertically into two horizontal layers based on the position of the pycnocline, which, during times of obvious stratification, was interpreted to be the midpoint in depth of the pycnocline. During early spring and fall, when stratification was not well developed, salinity profiles were used to choose a vertical boundary.

Horizontal limits of each box were defined by the midpoints between adjacent current meter arrays. For arrays lying at an endpoint of a transect, we used a distance beyond the array, equal to half the distance from the preceding array. Hence, any changes in the cross-sectional area of a given flux box between cruises were due to changes in depth of the pycnocline.

The bottom boundary for each box was the seafloor as determined by cross-sectional profiles of each transect, derived from the bathmetric map. A single bottom profile was used for each transect throughout all seven cruises. No SPM samples were obtained during cruise Neph 3 because of equipment failure. This assumes that changes in boxed areas due to small changes in bottom topography and station locations were negligible for the sampling period (March-September, 1979).

Once the boxed areas were defined, the average of all concentration values within a box was calculated and multiplied by the average current speed (surface or bottom) over the two-day sampling period. Thus, flux was defined as average speed (in cm/sec) times average concentration (in g/cm^3) and has units of mass per unit area per unit time.

3. RESULTS AND DISCUSSION

3.1 Hydrographic Data: Sigma-t Profiles

Conductivity and temperature data, obtained from continuous CSTD profiles sampled at one-meter intervals, were used to obtain cross sections of density values in units of sigma-t (σ_t). Sigma-t is defined as (density -1.000) x 1000.

The data reflect the usual stratification conditions found in the New York Bight. Comparison of the density data with data in Bowman (1978) shows very good agreement. Bowman's data, obtained in August 1976, shows the plume spread out over the Bight apex with complex interdigitations. With the exception of cruise Neph 2, the plume is not clearly seen. Cruise Neph 1 shows higher density values overall and minimal stratification, which is indicative of winter mixing in the water column. A thin lens of slightly

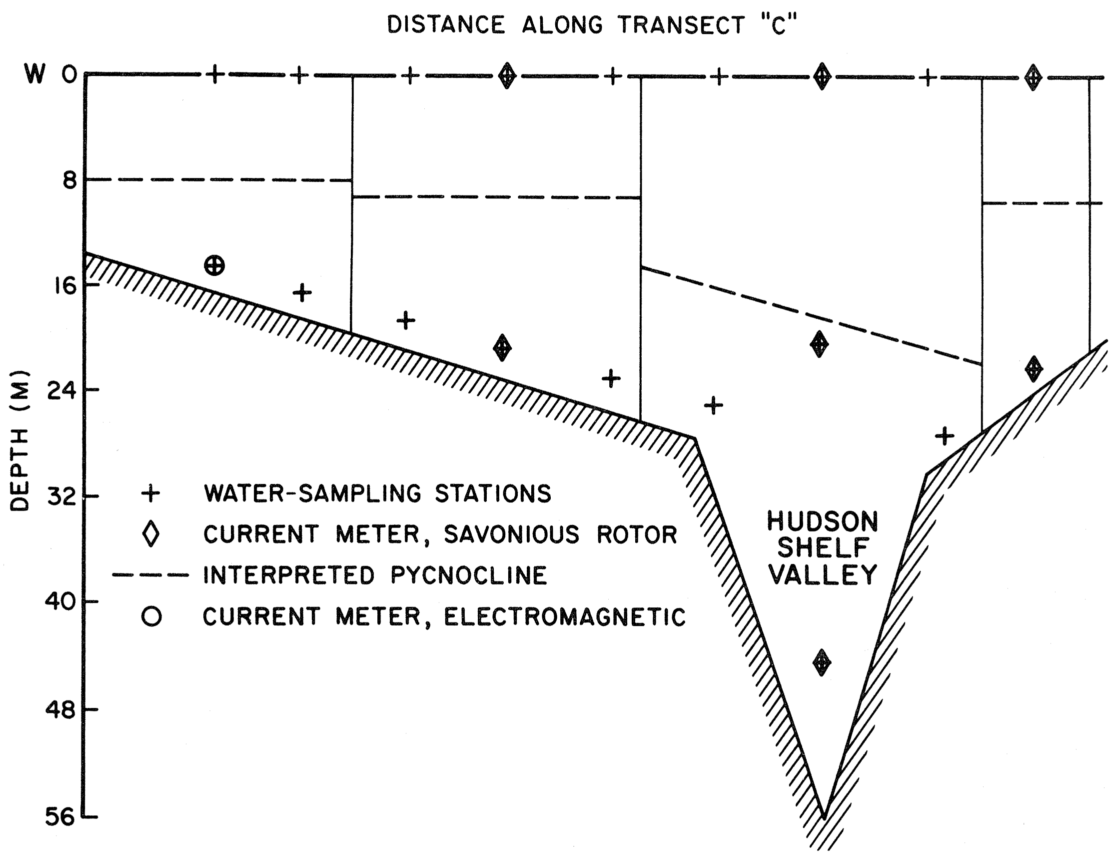

Figure 5. Example of cross section showing windows used in flux calculations. Transect is normal to the New Jersey shoreline. (See Figure 1 for transect scale.)

lighter water is seen consistently at the surface near the stations corresponding to the shelf valley (Figure 6, transect C).

The freshwater plume was seen best during cruise Neph 2 (April) along transects C, D, and E, normal to the New Jersey shore in the the form of a well-defined density front (Figure 6). The salinity data show an increase in salinity (from $\sim$25 to 31°/oo) both seaward along the transects and vertically toward the bottom waters. Temperature changes were slight supporting the hypothesis that the density front originates from salinity effects due to mixing of fresher river-plume waters with more saline shelf waters.

3.2 Suspended Particulate Matter Concentrations: Spatial and Temporal Distributions

Spatial distributions of surface and bottom SPM concentration values were plotted and contoured and are presented in Figures 7 and 8 for all cruises. Local areas of high concentration are seen in the expected location of the plume along the New Jersey coastline and generally along the Long Island coast. The March-April peak period of Hudson River discharge correlates well with the high surface values during cruises Neph 1 and 2.

Concentration contours for cruises Neph 1, 2, and 4 show local divergence to seaward along the New Jersey shore at the southern end of Sandy Hook (Figure 7). This pattern is presumed to be caused by Shrewsbury Rocks, a field of boulders projecting seaward from the beach to about the ten-meter isobath. These rocks cause a major change in the local bottom roughness, presumably increasing flow turbulence, vertical mixing, and resuspension.

Cruise 8 shows the expected increase in SPM concentrations after a brief (12-hour) and mild storm which is also reflected in the bottom concentrations. Cruises Neph 5, 6, and 7 represent a period of calm and have relatively low surface concentration values. This stable period is caused by a combination of events: a minimum in the runoff cycle, which limits SPM concentrations by a reduction in river input; a period of calmer weather where the frequency of resuspension by waves is also at a minimum; and a maxima in stratification when mixing is minimal.

Plots of bottom concentration values (Figure 8) show that concentrations during cruises Neph 1, 2, and 4 are slightly higher relative to the other cruises and may be related to the runoff cycle. The divergence of concentration contours at Shrewsbury Rocks seen in surface observations is also evident in the bottom plots. The Long Island coast has the highest values (10-12 mg/ℓ) for cruises Neph 2 and 4, a time of maximum runoff. It is possible that coastal lagoons along the Long Island coast experience seasonal flushing through estuarine inlets, similar to the runoff-flushing of the Hudson estuary. A similar influence may be produced at inlets along the New Jersey shoreline. However, these effects, are probably not significant when compared with resuspension by storm waves. SPM concentrations after a storm that occurred during cruise Neph 8 (Figures 7 and 8) show a twofold to fivefold increase in surface and bottom samples.

Spatially averaged concentrations of all surface and bottom samples for each cruise (shown in Figure 9), are divided between New Jersey and Long

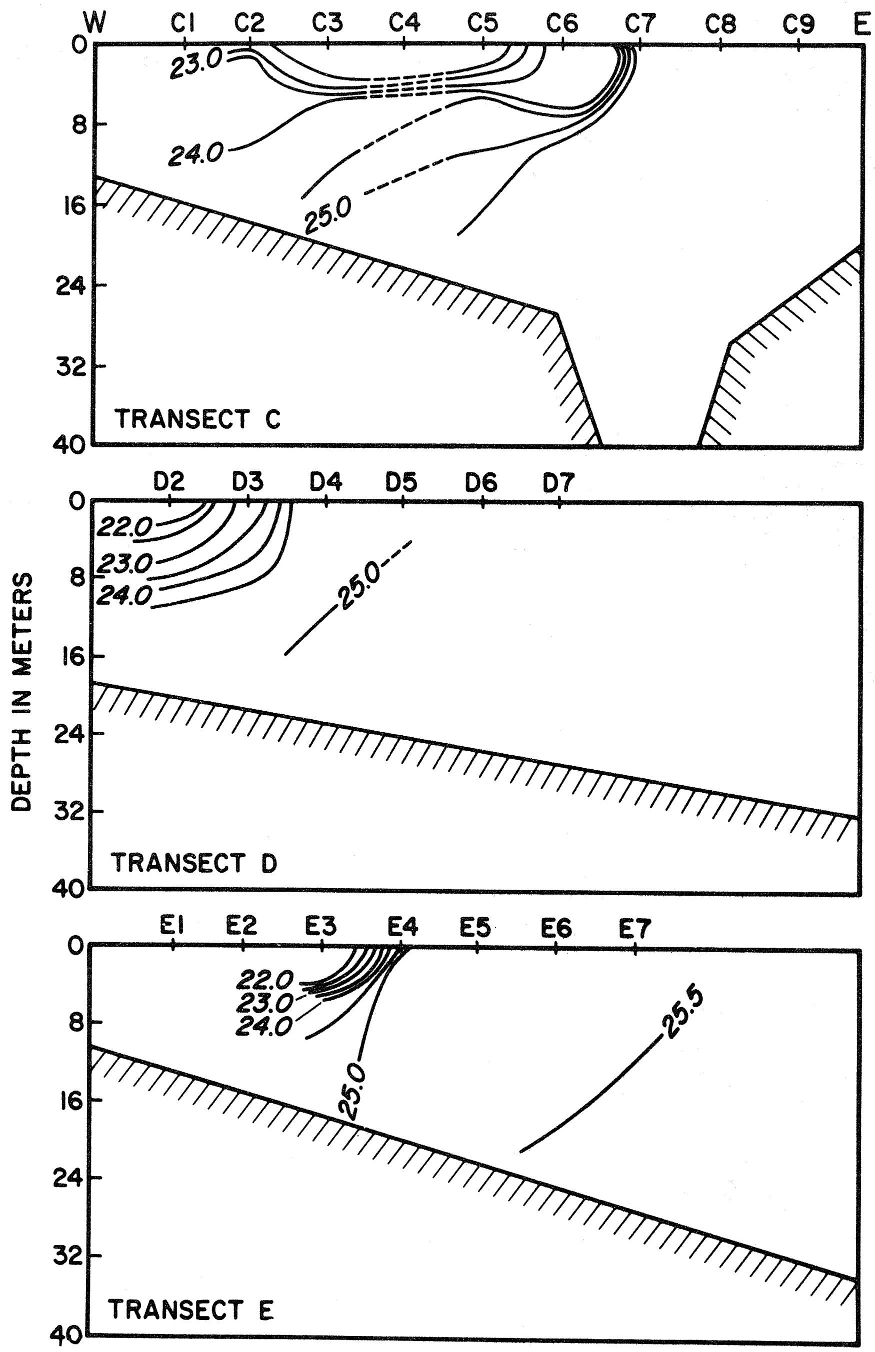

Figure 6. Sigma-t cross sections showing the Hudson plume during cruise Neph 2 (April 1979) (units are in sigma-t). The transects are not to scale horizontally (see Figure 1).

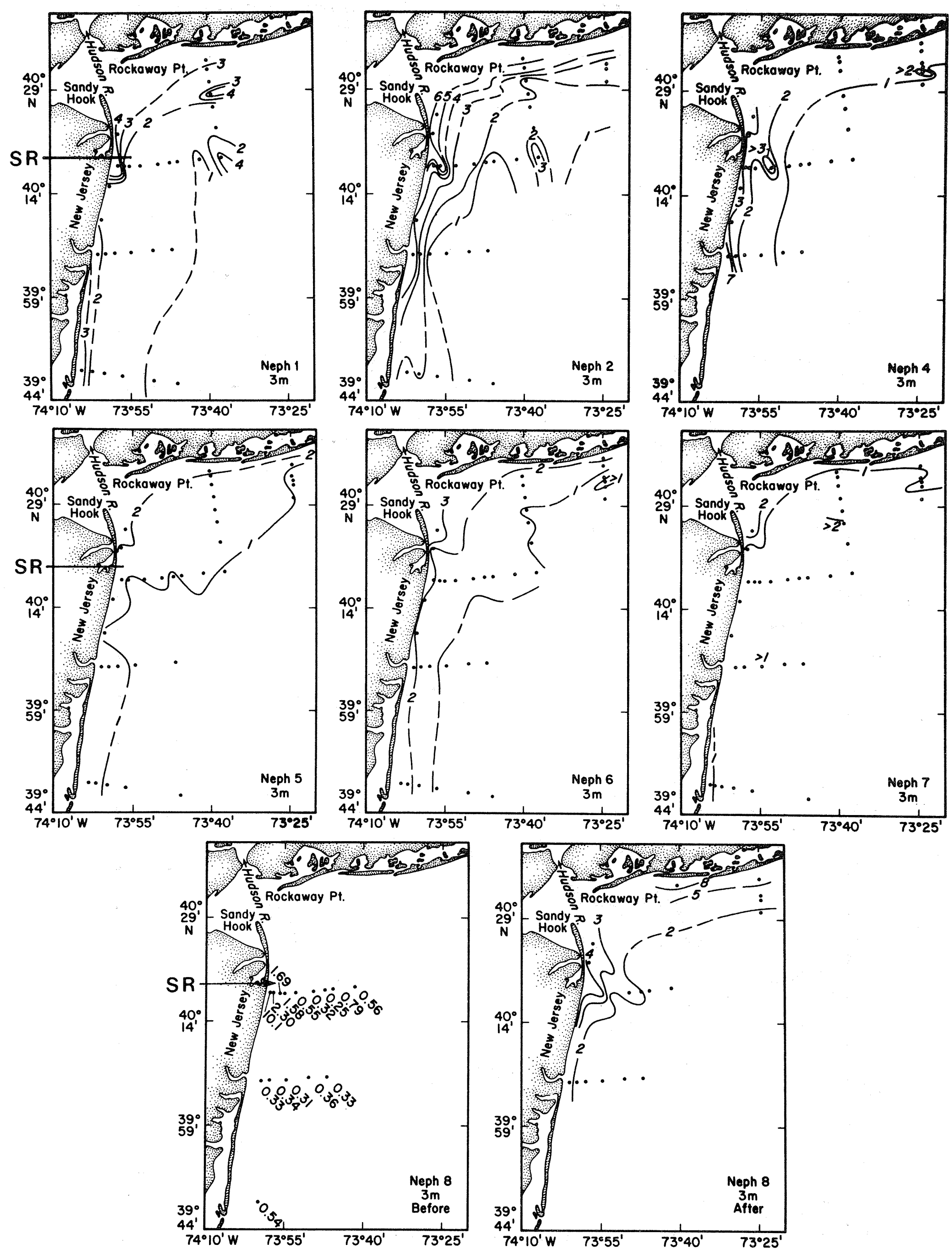

Figure 7. Contours of near-surface (3m) SPM concentration values in mg/ℓ. (See Table 1 for cruise dates. SR = Shrewsbury Rocks.)

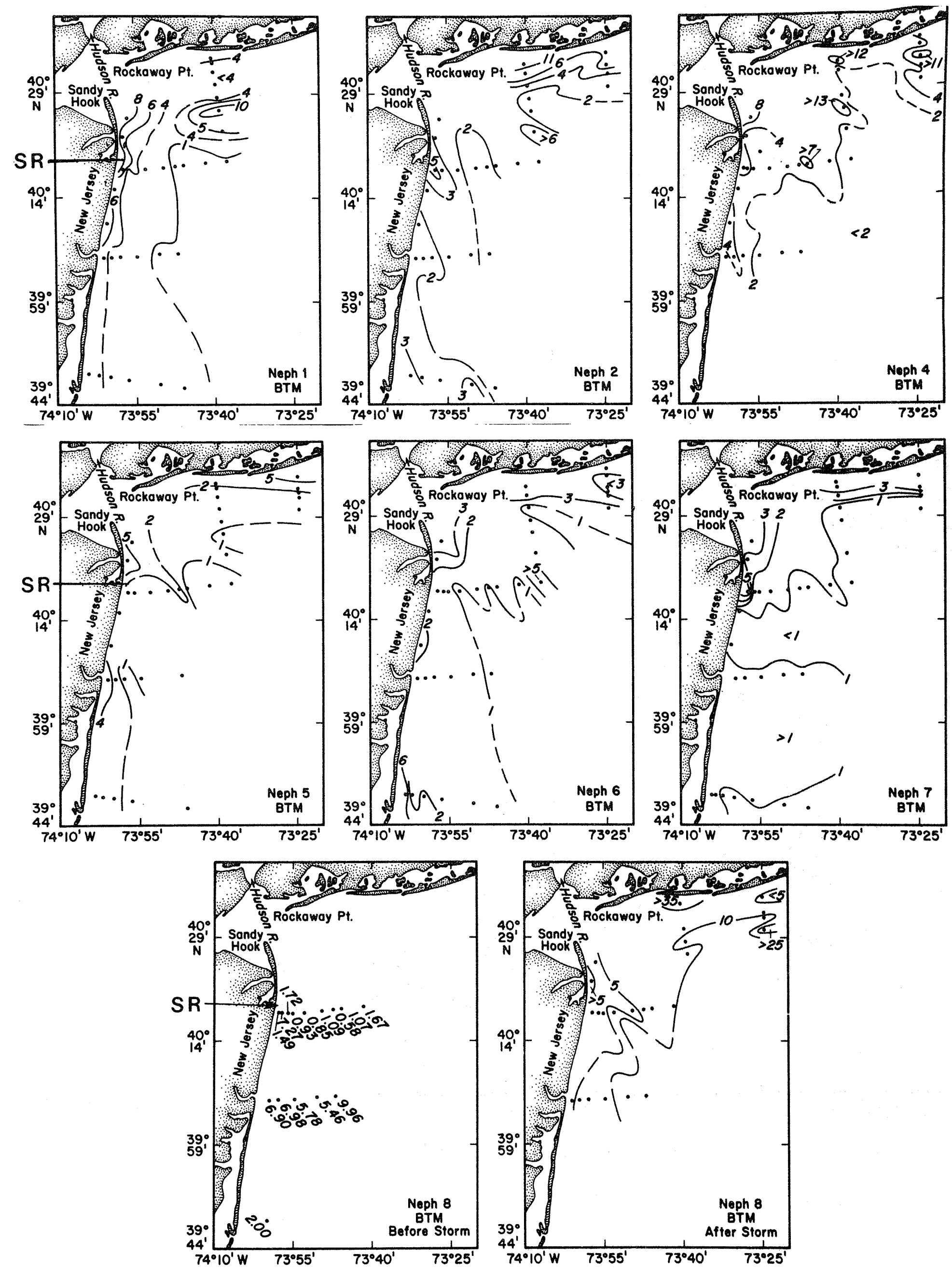

Figure 8. Contours of bottom SPM concentration values in mg/ℓ. (See Table 1 for cruise dates. SR = Shrewsbury Rocks.)

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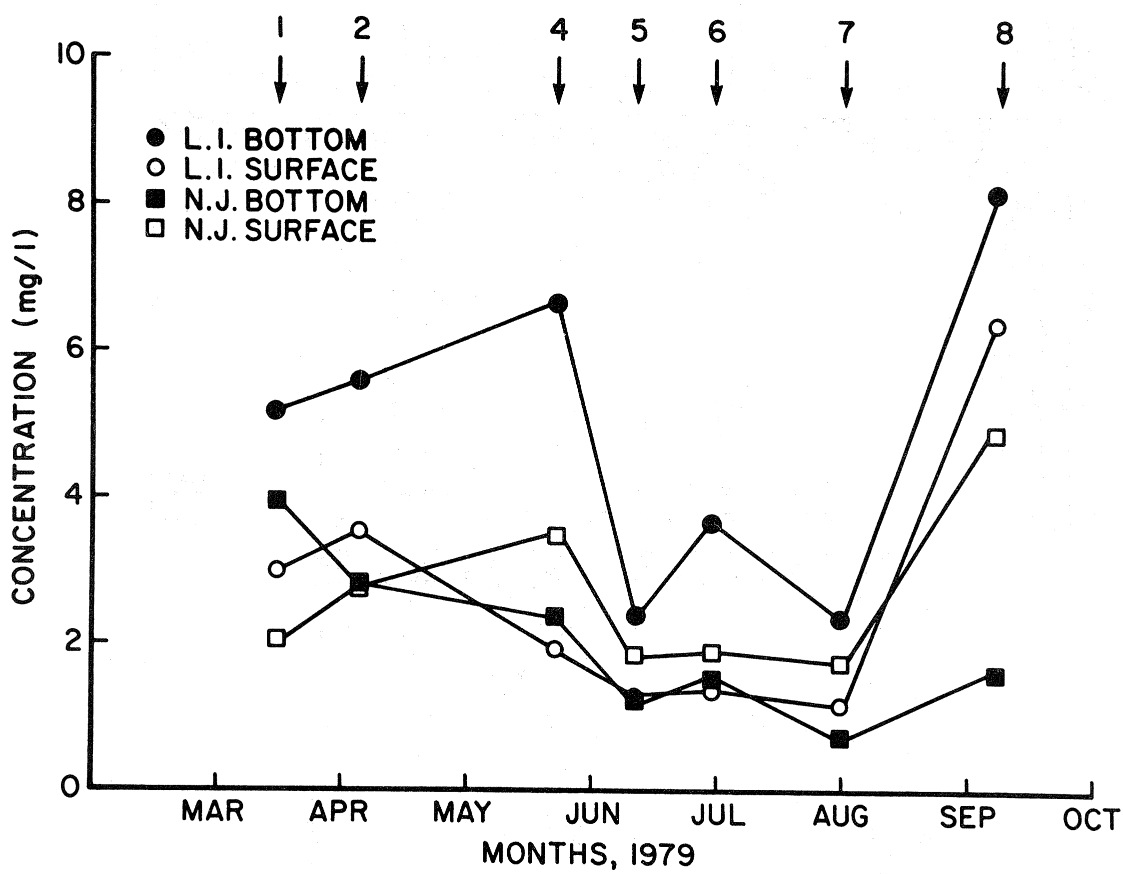

Figure 9. Average suspended matter concentrations for each cruise at near-surface and bottom for Long Island and New Jersey. Values for Long Island (L.I.) were obtained from transects A and B while New Jersey (N.J.) values were from transects C, D, and E. (See Figure 1 for transect locations.)

Island on the basis of transects (see Figure 1). New Jersey consists of the shore-normal transects C, D, and E. Long Island is defined as shore-normal transects A and B. At first glance, one sees the same trends shown on the Hudson River discharge plot (Figure 4). Values for Neph 8 are strongly influenced by the storm which occurred during the cruise (Figures 7 and 8). The weak response of the New Jersey SPM concentration to the storm may be due to the greater average depths along the New Jersey coast compared to the Long Island coast and the westerly direction of the storm winds. Winds from the west have limited fetch to develop waves and bottom resuspension as compared to the longer fetch and east-west orientation of the Long Island shore. Long Island bottom SPM concentration values are well above the others. Long Island and New Jersey surface concentrations were about equal. New Jersey surface concentrations were typically higher than New Jersey bottom concentrations, probably reflecting the contribution of suspended particulate matter from the plume migrating southward along the coast. Long Island bottom and surface concentrations were distributed in the opposite sense: higher bottom than surface values. This could be attributed in part to the absence of a large estuarine source for surface SPM on the Long Island coast, but it is also likely associated with wave resuspension effects on the shoaler Long Island coast. Surface and bottom concentrations along New Jersey were similar during Neph 2 (Figures 7 and 8) despite the strong density structure associated with the Hudson River plume (Figure 6). However, average concentrations were not especially high in comparison with other cruises.

3.3 Current Velocities

Tables 2 and 3 present average current speeds and directions for each two-day cruise period. Figures 10 and 11 are map-view plots of flux and can be used to infer current directions (but not speeds), since flux directions are current directions. A combination of the velocity tables and these plots can be used to determine whether concentration levels or current speeds are responsible for the resultant fluxes.

There are seven instances of flow divergence of nearly 180° between surface and bottom meters at the same station. These occur mostly along the New Jersey coast at the inshore-most Aanderaa meters (N31, N41, and N51). Surface currents along the New Jersey coast near shore were either reinforced by winds from the north (cruise Neph 2) or very weak. Weak currents were more typical during times of minimum runoff, but cruise Neph 1 shows the surface flow in opposition to the wind direction. However, the resultant surface current is small compared to cruise Neph 2, where the wind is slight but toward the plume's usual southerly set. It is probable that winds from the south tend to slow surface flow, if not reverse it.

Coherence among surface flow directions is better than among bottom meters, especially along the three New Jersey transects, C, D, and E. This is to be expected, since long-term deployments of bottom current meters have revealed many instances of incoherent bottom flow directions throughout the Bight (Han and Mayer, 1981).

Correlation between surface currents and winds was also limited by the observed wind strengths. None of the average winds exceeded 5 m/sec, or $\sim$.45 dynes/cm^2 of wind stress, velocities perhaps too weak to dominate

Table 2. Average Current Velocity and Direction, Upper Layer

Station	Transect	Neph Cruise Number 1	2	4	5	6	7	8 Before	8 After
N14	A	----	----	----	8.80	7.02	6.28	----	----
		----	----	----	199.30	231.00	166.40	----	----
N13	B	----	27.97	4.21	11.24	1.75	----	----	----
		----	107.90	132.80	209.60	47.10	----	----	----
N23	B	----	4.04	7.35	----	----	3.65	----	----
		----	208.60	134.70	----	----	293.60	----	----
N31	C	16.36	12.71	6.20	----	----	----	9.29	----
		195.10	183.30	223.60	----	----	----	208.90	----
N32	C	2.56	8.89	6.75	13.72	9.72	----	20.25	8.82
		283.30	168.00	356.30	195.20	118.80	----	49.50	289.00
N33	C(B)	----	8.63	21.48	11.14	2.42	9.96	9.10	1.18
		----	23.90	210.80	188.30	145.40	92.70	25.10	292.10
N41	D	9.48	10.48	8.81	9.41	17.31	6.63	10.53	16.23
		199.90	207.80	26.20	228.00	60.60	28.70	46.90	189.30
N42	D	16.95	25.36	13.56	7.67	8.13	----	----	----
		204.80	180.40	188.00	191.00	57.40	----	----	----
N51	E	----	30.40	----	----	21.95	10.91	17.73	7.29
		----	196.90	----	----	16.10	39.10	24.30	193.00
N52	E	19.65	10.83	----	14.28	16.21	----	----	----
		186.50	154.80	----	211.80	81.20	----	----	----

Key: 67.21 = magnitude (cm/sec)
35.10 = direction (degrees true)

Table 3. Average Current Velocity and Direction, Lower Layer

Station	Transect	Neph Cruise Number 1	2	4	5	6	7	8 Before	8 After
N14	A	---- / ----	---- / ----	---- / ----	3.56 / 223.20	12.78 / 216.90	7.39 / 239.20	6.92 / 176.90	4.10 / 174.10
N03	B	---- / ----	---- / ----	---- / ----	---- / ----	---- / ----	.90 / 94.00	1.69 / 62.50	---- / ----
N13	B	---- / ----	34.19 / 85.10	17.47 / 68.70	---- / ----	---- / ----	---- / ----	---- / ----	---- / ----
N23	B	---- / ----	2.57 / 335.40	5.27 / 110.00	1.19 / 311.80	7.90 / 264.60	---- / ----	---- / ----	---- / ----
N30	C	---- / ----	---- / ----	---- / ----	----- / ----	---- / ----	1.54 / 203.00	2.24 / 223.70	---- / ----
N31	C	12.88 / 25.00	12.64 / 225.60	9.72 / 45.80	3.67 / 160.90	19.43 / 210.20	---- / ----	5.50 / 73.60	---- / ----
N32	C	29.70 / 349.30	.82 / 199.30	7.65 / .30	6.30 / 349.30	.17 / 148.50	---- / ----	---- / ----	---- / ----
N32*	C	38.58 / 354.90	11.59 / 288.00	11.85 / 355.40	6.30 / 349.30	.17 / 148.60	---- / ----	4.99 / 207.30	5.92 / 231.80
N33	C(B)	---- / ----	---- / ----	---- / ----	5.96 / 68.40	9.93 / 201.30	---- / ----	---- / ----	---- / ----
N40	D	---- / ----	---- / ----	2.10 / 218.00	---- / ----	---- / ----	1.21 / 115.00	1.11 / 74.80	---- / ----
N41	D	10.07 / 281.70	6.55 / 231.70	4.41 / 18.10	--- / ---	12.74 / 222.30	12.60 / 233.20	9.46 / 275.60	7.96 / 179.10
N42	D	---- / ----	---- / ----	---- / ----	5.58 / 94.10	3.52 / 179.80	---- / ----	---- / ----	---- / ----
N51	E	---- / ----	7.32 / 236.80	---- / ----	---- / ----	2.43 / 214.80	10.06 / 198.20	2.31 / 314.90	14.04 / 163.10
N52	E	14.14 / 100.80	6.72 / 108.80	---- / ----	11.25 / 100.20	9.97 / 104.30	5.55 / 218.00	2.10 / 216.80	8.42 / 177.50

Key: 67.21 = magnitude (cm/sec)
35.10 = direction (degrees true)

*Midwater current meter (Hudson Shelf Valley)

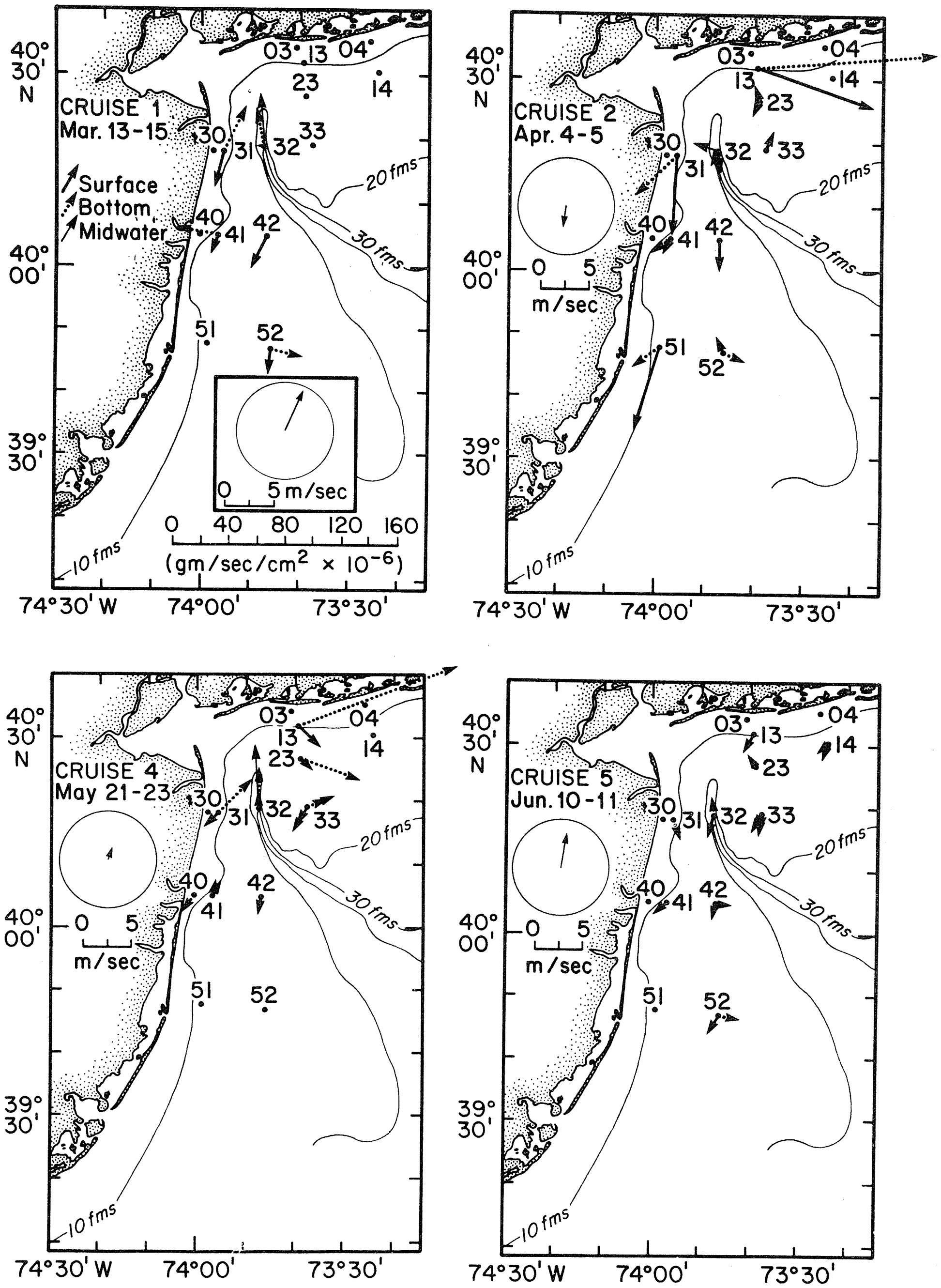

Figure 10. Vectors of SPM flux for cruises Neph 1, 2, 4, and 5 also showing average wind vectors from John F. Kennedy Airport, New York. Refer to cruise Neph 1 for SPM flux scale.

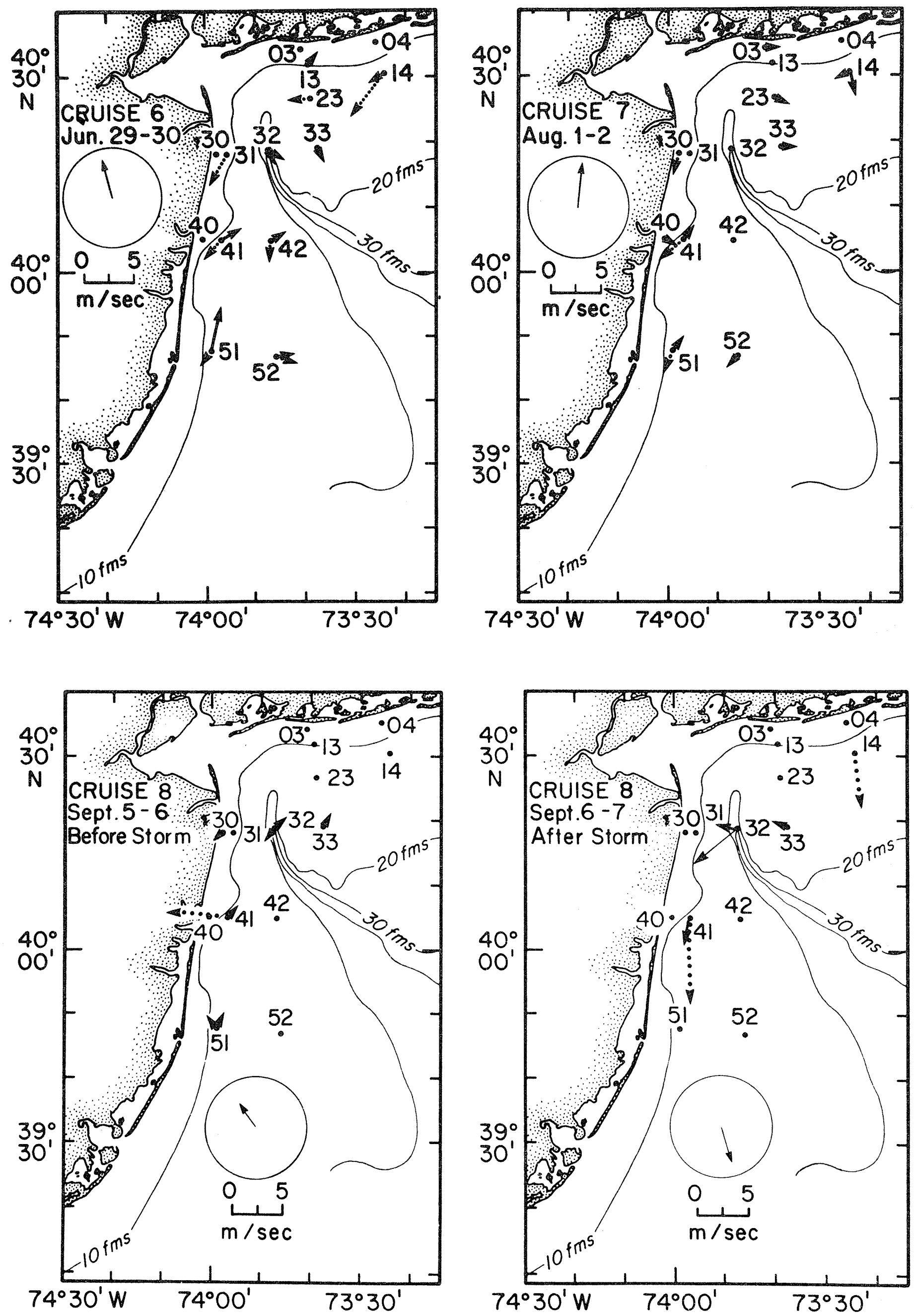

Figure 11. Vectors of SPM flux for cruises Neph 6, 7, 8 (before the storm), and 8 (after the storm). Also shown are average wind vectors from John F. Kennedy Airport, New York. Refer to cruise Neph 1 for flux scale.

the advective forces which drive the flow (Han and Mayer, 1981). Winds during the storm that occurred during Neph 8 were excluded from the average.

3.4 Flux Interpretations

Tables 4 and 5 and Figures 10 and 11 present surface and bottom values of SPM flux in gm/sec/cm^2 (x 10^{-6}). The directions are given in degrees true and are directly from the observed average current directions. Stations lacking either a concentration value or current velocity are shown by dashes. Certain stations were not sampled for SPM due to operational constraints. Also, cruises Neph 1 and 8 (before the storm) have SPM concentration values only for the New Jersey transects. The reader is referred to Figure 3 for times of current meter records.

The year 1979 was one of very few transport events. Highest values of both fluxes and concentrations occurred during cruises Neph 1, 2, and 8. This is shown by the averaged concentrations (Figure 9) and by the seasonal variation in overall flux magnitudes averaged over each cruise. Figure 12 shows cruise-averaged flux magnitudes for each cruise based on the values in the flux tables. As in Figure 9, it should be noted that the solid lines connect cruise-mean values and only roughly approximate trends between cruises. Sampling during cruise Neph 8 shows the effect of one small storm on SPM concentration in the Bight. High values of flux (cruise Neph 1) are clearly attributable to river runoff, but a short-lived storm, such as occurred during cruise Neph 8, causes SPM concentrations to reach levels similar to those during runoff. This agrees with prior studies (Lavelle et al., 1979; Young et al., 1981; Clarke et al., 1982) that show storms are the major events regulating levels of suspended matter in the Bight.

The plume signature is clearly seen during cruise Neph 2 at the surface of current meter stations N31, N41, and N51. Inspection of the data (Table 2; Figure 7) show these stations to be high in velocity but relatively low in concentration of suspended matter. This suggests that one is seeing the hydrographic and dynamic effects of the plume, and the high suspended matter flux is due mainly to increased flow, not to increases in SPM associated with the peak period of runoff.

Since the water density signature of the plume was strongest during cruise Neph 2, one might also expect to see high values for surface concentration from increased river runoff. This was not observed suggesting that while the plume is certainly a major mechanism for suspended matter transport, it has limited effect on SPM concentration. Thus, the flux of suspended matter along the New Jersey coast is likely due to the increased current velocities at the surface and not to any large increases in the concentration of river-derived sediment. Suspended matter in the plume is probably maintained by turbulence and wave mixing. Wave resuspension seems to be the main mechanism affecting near-bottom suspended matter concentrations in other parts of the New York Bight (Lavelle et al., 1979; Young et al., 1981; Lesht et al., 1981).

4. SUMMARY AND CONCLUSIONS

This investigation of the SPM related to the Hudson-Raritan estuarine plume has shown that SPM signatures are weak during most of the year except

Table 4. Average SPM Flux Above the Pycnocline (or Halocline)

Station	Transect	Neph Cruise Number							
		1	2	4	5	6	7	8 Before	8 After
N14	A	---- / ----	---- / ----	---- / ----	$\frac{7.3}{199}$	$\frac{6.9}{231}$	$\frac{12.1}{166}$	---- / ----	---- / ----
N13	B	---- / ----	$\frac{85.3}{108}$	$\frac{20.3}{133}$	$\frac{15.2}{210}$	$\frac{2.8}{47}$	---- / ----	---- / ----	---- / ----
N23	B	---- / ----	$\frac{7.2}{209}$	$\frac{7.6}{135}$	---- / ----	---- / ----	$\frac{5.7}{294}$	---- / ----	---- / ----
N31	C	$\frac{25.2}{195}$	$\frac{58.5}{183}$	$\frac{14.8}{224}$	---- / ----	---- / ----	---- / ----	---- / ----	---- / ----
N32	C	$\frac{3.1}{283}$	$\frac{11.9}{168}$	$\frac{5.9}{356}$	$\frac{16.3}{195}$	$\frac{12.4}{118}$	---- / ----	$\frac{8.3}{50}$	$\frac{13.2}{289}$
N33	C(B)	---- / ----	$\frac{12.1}{24}$	$\frac{12.0}{211}$	$\frac{11.4}{188}$	---- / ----	$\frac{.8}{93}$	$\frac{3.9}{25}$	$\frac{.9}{292}$
N41	D	$\frac{14.1}{200}$	$\frac{3.4}{208}$	$\frac{9.2}{26}$	$\frac{8.8}{228}$	$\frac{16.4}{61}$	$\frac{7.6}{29}$	$\frac{3.9}{47}$	$\frac{17.1}{189}$
N42	D	$\frac{25.4}{205}$	$\frac{19.8}{180}$	$\frac{8.0}{188}$	$\frac{5.9}{191}$	$\frac{6.6}{57}$	---- / ----	---- / ----	---- / ----
N51	E	---- / ----	$\frac{61.7}{197}$	---- / ----	---- / ----	$\frac{36.4}{16}$	$\frac{6.8}{39}$	$\frac{9.8}{24}$	---- / ----
N52	E	$\frac{17.1}{187}$	$\frac{7.2}{155}$	---- / ----	$\frac{8.3}{212}$	$\frac{9.2}{81}$	---- / ----	---- / ----	---- / ----

Key: $\frac{67.2}{35}$ 67.2 = magnitude (x 10^{-6} g/sec/cm^2); 35 = direction (degrees true)

Table 5. Average SPM Flux Below Pycnocline (or Halocline)

Station	Transect	Neph Cruise Number 1	2	4	5	6	7	8 Before	8 After
N14	A	---- ----	---- ----	---- ----	6.3 223	34.6 217	9.2 239	---- ----	37.5 174
N03	B	---- ----	---- ----	---- ----	---- ----	---- ----	4.3 94	---- ----	---- ----
N13	B	---- ----	123.1 85	120.2 69	---- ----	---- ----	---- ----	---- ----	---- ----
N23	B	---- ----	4.2 335	44.1 110	3.0 312	12.7 265	---- ----	---- ----	---- ----
N30	C	---- ----	---- ----	---- ----	---- ----	---- ----	8.2 203	7.7 224	---- ----
N31	C	35.7 25	41.1 226	33.1 46	9.8 161	22.3 210	---- ----	---- ----	---- ----
N32	C	29.1 349	1.3 199	29.0 0	6.3 349	.3 149	---- ----	---- ----	---- ----
N32*	C	37.8 355	18.5 288	44.9 355	---- ----	---- ----	---- ----	35.6 232	4.5 207
N33	C(B)	---- ----	---- ----	---- ----	19.6 68	7.6 201	---- ----	---- ----	----
N40	D	---- ----	---- ----	7.0 218	---- ----	---- ----	2.2 115	1.0 75	---- ----
N41	D	26.9 282	12.1 232	7.6 18	---- ----	15.5 222	16.6 233	42.6 276	59.1 179
N42	D	---- ----	---- ----	---- ----	8.3 94	7.9 180	---- ----	---- ----	---- ----
N51	E	---- ----	21.5 237	---- ----	---- ----	7.5 215	12.0 198	4.6 315	---- ----
N52	E	24.5 101	16.3 109	---- ----	8.8 100	13.0 104	2.1 218	---- ----	---- ----

Key: 67.2 = magnitude (x 10^{-6} g/sec/cm^2)
35 = direction (degrees true)

*Midwater current meter (Hudson Shelf Valley)

NEPH CRUISE NUMBER

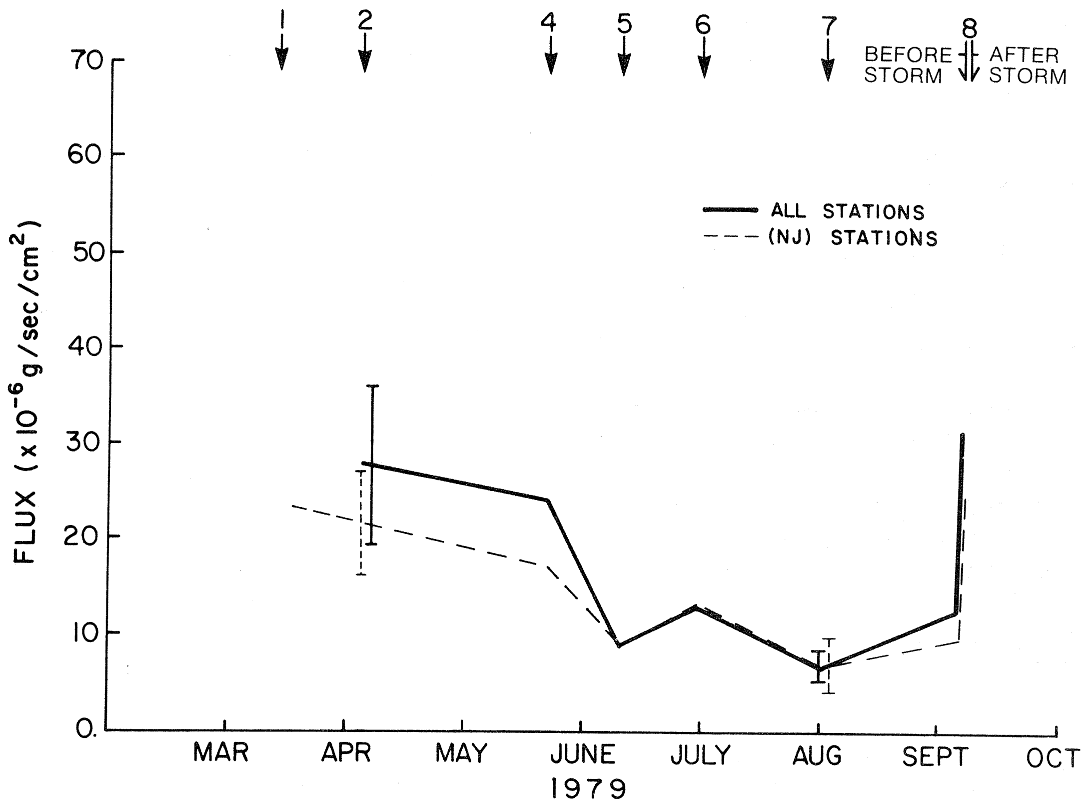

Figure 12. A comparison of average magnitudes of SPM flux for each cruise. Standard error of the mean (slightly offset for clarity) is shown for cruises Neph 2 and 7. New Jersey stations (transects C, D, and E) are shown separate for comparison. The two data points in September (cruise Neph 8) represent before and after storm values.

during peak river runoff in early spring. At other times storm wave resuspension may create high concentration levels of SPM along shore which may then be advected as a particulate plume. This redistribution process may account for the apparent lack of accumulation of fine sediments along the New Jersey shore in the path of the estuarine SPM plume.

Unfortunately, only one cruise (Neph 1) took place during the winter storm season (November-March). Other cruises (except cruise Neph 8) reflect quieter and more stable spring and summer conditions in the Bight. Not only was 1979 an uneventful year, but the four middle cruises (Neph 4, 5, 6 and 7 show almost no change in both current velocities and concentrations.

Some regional trends of suspended particulate matter in the apex were found along with aspects of the plume's spatial and temporal behavior:

(1) Long Island bottom waters are generally richest in suspended particulate matter. This may be due primarily to the broad, shallow shelf of this area which offers more opportunity for resuspension by orbital currents from incoming waves.

(2) Concentrations of suspended particulate matter along the New Jersey shoreline are surface-dominated, presumably as a result of the estuarine plume. Concentrations of suspended matter in the surface plume waters were usually higher than those in the Long Island surface waters or in the New Jersey bottom waters underlying the plume. New Jersey surface concentrations were lower than expected during cruises Neph 1 and 2 when river runoff was at a seasonal maximum, while bottom waters were richer in suspended matter. Settling of particles from the surface into the bottom waters may account for this distribution, but the strong halocline would seem to mediate against this.

(3) A seasonal minimum and maximum in suspended particulate matter concentrations correspond closely to the Hudson River runoff cycle. However, the high average concentrations of cruise Neph 1 during March may also be related to the winter storm season when resuspension and discharge from the estuary can assume magnitudes equal to the storm in cruise Neph 8.

(4) Only in April (cruise Neph 2) during peak runoff was the signature of the plume seen clearly in the form of a sharp density front along the current meter transects. During cruise Neph 2 the plume was seen in all three New Jersey transects, decreasing in volume southward. More water sampling within the plume itself may have yielded better results during other cruises, though the seasonal approach best shows the effects of transition from a time of mixing (winter) to a time of maximum stratification (summer). The plume hydrographic and SPM signal decreases rapidly with distance from the estuary mouth at all other times of year.

(5) The study reaffirms the hypothesis that storm waves are the dominant mechanism causing resuspension in the Bight as shown by cruise Neph 8 in Figures 9 and 12.

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